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Final Report

OFFICE OF NAVAL RESEARCH

For Contract N00014-86-K-0085 on

GEOMAGNETIC DISTURBANCES

For the Period
October 1, 1985 to September 30, 1988

January 1989

LELAND STANFORD JUNIOR UNIVERSITY
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CENTER FOR SPACE SCIENCE AND ASTROPHYSICS
STANFORD UNIVERSITY
Stanford, California

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For Contract N00014-86-K-0085 on

GEOMAGNETIC DISTURBANCES

For the Period
October 1, 1985 to September 30, 1988

January 1989

Submitted by:

Philip H. Scherrer
Center for Space Science and Astrophysics
Stanford University
Stanford, California 94305-4055
(415)723-1504

Foreword

This is the final report for research on the origins of "Geomagnetic Disturbances" supported under The Office of Naval Research, Contract N00014-86-K-0085 under the direction of Prof. Philip H. Scherrer. The research has been carried out at the Center for Space Science and Astrophysics and the Wilcox Solar Observatory at Stanford University, Stanford, California.

Contents

Final Report of Naval Research

Contract N00014-86-K-0085

GEOMAGNETIC DISTURBANCES

This is the final report on research on the causes of "Geomagnetic Disturbances" for the interval October 1985 through September 1988. At the beginning of the interval, Dr. Philip H. Scherrer was PI and Prof. Peter A. Sturrock was a co-investigator. Beginning in October 1987 the work was directed solely by Prof. (Research) Scherrer. For the interval under consideration, the WSO research group consisted of Philip H. Scherrer, J. Todd Hoeksema, and Richard S. Bogart (research group) and Harald M. Henning, Marc Herant, and Bernard Gelly (students). Henning completed his Ph.D. work in December 1987 and is now working in Germany. Herant is now a graduate student at Harvard. Gelly, who was here as a post-doctoral student, has returned to France.

Our investigations have included observations and analysis of the solar and interplanetary quantities relevant to geomagnetic activity. The operation of the John M. Wilcox Solar Observatory (WSO - formerly the Stanford Solar Observatory) and analysis of the synoptic observations of magnetic fields has constituted a significant part of the effort. We have also been increasing our joint efforts with Peter Sturrock's group at Stanford, with particular attention to the work being pursued by Taeil Bai

The emphasis of our research has been to attempt to understand the timing and severity of geomagnetic disturbances by understanding the solar mechanisms responsible for the origin of solar wind variations. The detailed reports of our progress are to be found in the publications of the WSO group and in the renewal proposals for the intermediate years.

For ease of access, I have included here as Appendix A the text from the renewal proposal in 1986 which describes work done during the first year of the contract. I have included as Appendix B the report sent to Neil Sheeley, our Scientific Program Officer, by electronic mail in August 1987. That report is a short summary of work in the second year. I have also included the text from the proposal submitted in May 1988 which is presently funded under Contract N00014-89-J-1024. That proposal describes work done in the final year of this contract.

In the several months between the submission of Appendix C as a proposal and the end of the contract, we continued the investigations described in that Appendix.

Appendix D contains to date a complete listing of publications and technical reports resulting from work supported by this contract.

Proposal to

OFFICE OF NAVAL RESEARCH

To Renew Contract N00014-86-K-0085 on

GEOMAGNETIC DISTURBANCES

For the Period
October 1, 1986 to September 30, 1988

Proposal No. SEL100-86

June 1986

Submitted by:

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Foreword

This is a proposal for continuation of the Geomagnetic Disturbance research and the operation/maintenance of the Wilcox Solar Observatory under the direction of Dr. Philip H. Scherrer as Principal Investigator, and Professor Peter Sturrock as co-investigator at the Center for Space Science and Astrophysics at Stanford University, Stanford, California under Office of Naval Research Contract N00014-86-K-0085. Support is requested for a two year period beginning October 1, 1986, and ending September 30, 1988 in the amount of $80,000 per year.

Proposal for Continuation of Naval Research

Contract N00014-86-K-0085

GEOMAGNETIC DISTURBANCES

Introduction

This proposal is a request for support to continue our investigations of the causes of geomagnetic disturbances. Our investigations include observations and analysis of the relevant solar and interplanetary quantities. The operation of the Wilcox Solar Observatory and analysis of the synoptic observations of magnetic fields constitutes a significant part of the effort. The emphasis of our research continues to be to attempt to understand the timing and severity of geomagnetic disturbances by understanding the solar mechanisms responsible for the origin of solar wind variations. Based on what has been learned and on the availability of our growing set of solar magnetic and velocity observations, we believe that we can continue to make substantial progress in this area. The present efforts are concentrated in several areas of research.

There is little doubt that magnetic field evolution is directly related to most if not all solar variability. Solar magnetic fields are organized on several spatial scales. While some of the solar variability is controlled by field changes on small-scales, the largest scales of organization are responsible for structuring the corona and solar wind expansion. It is also evident that small-scale activity is organized into larger-scale centers of activity. Understanding the relation between the development of solar activity and the evolution of the large-scale patterns of fields is an important part of our research effort. Our solar magnetic field synoptic observing program is dedicated to obtaining data necessary to understand the source and evolution of the relevant fields.

The "static" structure of the corona is determined by the large-scale organization of photospheric fields. During times of low activity, these fields can be used to infer the coronal structure and the form of the heliospheric current sheet with reasonable accuracy. During times of high activity, the large-scale fields produce the ambient structure of the solar wind and interplanetary field into which transient material is injected. We are continuing our study of the origin and structure of coronal magnetic fields and the origin of solar wind variability.

A statistical relation exists between the locations and importance of transient events such as large flares and the large-scale magnetic structure. There is also an apparent relation between the solar wind disturbance produced by a transient and its location relative to the heliospheric current sheet. We are investigating these relations between transient events and the large-scale ambient structure. We plan to look both at the relation between the ambient structure and the times and locations of transients, and at the apparent effect of the heliospheric current sheet structure on propagation characteristics.

A knowledge of the structure of the solar convection zone and the global circulation is crucial to understanding the large-scale organization of magnetic fields and the eventual understanding of the solar magnetic cycle. One of our observational efforts has been an attempt to directly observe the surface manifestations of giant scale convective motions. Our 10-year series of Dopplergrams provide upper limits to the observable amplitudes of these elusive motions.

Our recent progress and proposed investigations in each of these areas will be discussed below.

Large Scale Magnetic Fields

In previous work we have shown that the large-scale solar field, as revealed by the mean solar field and by the polarity structure of the interplanetary magnetic field, is organized into patterns with recurrence periods of both 27 and about 28.5 days (Svalgaard and Wilcox, 1975). We have shown that the 27-day pattern originates in lower latitudes (Svalgaard et al., 1975) while the slower pattern is evident at higher latitudes (Hoeksema, 1984). In fact, the largest-scale patterns can be described as a low latitude "four-sector" pattern with a 27-day (synodic) rotation, a mid-latitude "two-sector" (not always symmetric) pattern with a 28/29-day rotation, and the polar fields. The solar cycle evolution of the largest-scale patterns can be modeled by the changing flux in these basic patterns.

Recently (Sheeley and DeVore, 1986) have shown that the 28/29-day structure can be maintained by flux injected at lower latitudes and carried to higher latitudes by diffusion and/or meridional circulation. In this model the particular strength and longitude distribution of the slowly rotating structure depends on the details of the source regions. If this model is correct, we need to know the relationship between the locations of the new flux and the 27-day pattern. We plan to investigate the relation between the 27-day large-scale pattern and the flux sources used by Sheeley and Devore as well as the superactive regions defined by

Bai (1986). The basic question is whether the 27-day pattern and the locations of active centers (active longitudes, or superactive regions) are determined by chance, or whether it is an indicator of a more fundamental large-scale circulation or internal magnetic structure?

We propose to continue our investigation into these questions by analyzing the now complete cycle of magnetic observations from the Wilcox Observatory along with magnetic observations from NSO and Mt. Wilson, and activity data from both ground-based observations and from SMM. Much of this work will be done in the framework of the Solar Cycle Workshops presently being organized.

Coronal and Interplanetary Magnetic Fields

The photospheric fields determine, to a large extent, the structure of the coronal and interplanetary magnetic fields. The solar wind originates in the solar corona. The variability of the solar wind at Earth arises from rotation of the sun and the changing conditions in the source region. One of our major research goals is to clarify the connection between the field observed on the solar surface and the characteristics of the interplanetary medium measured throughout the heliosphere.

To calculate the coronal field we employ a potential field - source surface model described in detail by Hoeksema (1984). From our photospheric field observations we calculate the three-dimensional field in the low corona between the photosphere and the source surface. Located at 2.5 solar radii, the source surface is the imaginary sphere at which all field lines are radial and open to the solar wind. Assuming a radial flow, the field structure propagates outward into the heliosphere along Archimedean spirals in a predictable way. A complete record of the photospheric and predicted coronal fields from 1976 to the present time was published during the past year as UAG Report 94 (Hoeksema and Scherrer, 1986). We anticipate that in addition to our own studies, these data will be useful in a wide variety of investigations concerning solar - terrestrial relations.

In order to improve our model of the 3-dimensional structure of the heliospheric current sheet, we need correlative data concerning high latitude structures. This data can come from both ground-based and space-based coronagraph observations. We hope to expand our efforts in this area by comparing the available Solwind, SMM, HAO, and Helios data with our computed source-surface field configuration. Our recent success in predicting sector-boundary crossings of comet Halley have suggested that comet tail

disconnections also may indeed provide another indicator of the three-dimensional structure of the current sheet.

A clear relationship exists between high-speed solar wind streams and coronal holes. Holes develop above large unipolar regions in the photosphere and within large unipolar regions in the corona. Can the existence or development of coronal holes or "virtual" holes be inferred from the photospheric or coronal magnetic field? Can high-speed solar wind also originate in unipolar regions not containing a coronal hole? A minimum in solar wind speed occurs at the current sheet and solar wind speed tends to increase with distance from the current sheet. Can we better quantify this relationship for both predictive purposes and for better comparisons with model calculations? We have begun to examine these questions for a limited time period near solar maximum (Suess et al., 1984) and some work has been done by Newkirk and Fisk (1985). Our first results were intriguing, showing a possible correlation between field strength computed on the source surface and solar wind velocity measured at Earth, but the detailed relationship was unclear because of the limited time interval and the number of activity related events. More work remains to be done and we intend to continue our investigations in this area.

The photosphere rotates differentially, but coronal holes rotate almost rigidly. At Earth we observe recurrent patterns in the interplanetary magnetic field (IMF) with periodicities of 27 days and 28 - 29 days. We are studying the rotation of the coronal field and the large-scale photospheric field to determine the origin of these differing rates and to study their effect on coronal structure. We find that, like coronal holes, the coronal field rotates much more rigidly than the photospheric field. This can be seen by visually comparing several consecutive coronal field patterns and by computing the rotation at different latitudes from the first peak in the autocorrelation. This result is consistent with work done by others, e.g. Fisher and Sime (1984), who have investigated the rotational characteristics of the white light corona from 1965 to 1983.

Closer inspection shows that the rates in the northern and southern hemispheres are significantly different. Spectral analysis of the field patterns at different latitudes during the current sunspot cycle shows that the northern hemisphere fields rotate with a period near 27 days while the southern fields show a pronounced peak in the 28 - 29 day range (Hoeksema and Scherrer, 1985; Hoeksema and Scherrer, 1986a). This contrasts with the results of Parker et al. (1982) who found a faster rotation rate in the southern

hemisphere during Solar Cycle 20. Many questions remain about the nature of the difference in rotation rates: Does it change during the cycle? Do the different IMF structures arise in different source regions? What is the relation between the coronal rotation and the locations and timing of new flux added to the photosphere by activity complexes? We plan to pursue these questions in future investigations.

Organization of Transient Events

In previous studies (Dittmer, 1975; Henning et al., 1985; Lundstedt et al., 1981) we have demonstrated statistical relations between the locations and importance of transient events such as large flares and the ambient magnetic structure. These investigations have raised a number of interesting questions. The main question is whether there is an interraction between the transients and the ambient medium, or whether there is a relation between the nature and timing of transient events and the ambient surface fields, or whether the statistical relations discovered are simply unlikely chance associations. The previous studies used available tabulations of important flares to study the statistical connections. It may also be useful to specifically examine coronal mass ejections as a class of events known to be important to the solar wind. Bai (1986) has tabulated a list of important flares based on SMM observations and other data for the most recent solar maximum. Use of this data would allow an extension of our analyses to include all of Solar Cycle 21.

In addition to extending the previous study and including other types of transients, the physical mechanism responsible for the statistical relation between flare disruption of the solar wind as observed at earth and the position of the heliospheric current sheet should be investigated. This should be done by examining the transients as they propagate through the ambient solar wind. This requires observations from spacecraft at several heliocentric distances. We plan to pursue this study when the required data can be collected and collated.

These questions also relate to our ongoing study of the relation between the locations of activity and the large-scale magnetic structure. We plan to investigate this relation by comparing the superactive regions identified by Bai (1986), the set of most important new flux centers identified by DeVore (1986), and the magnetic structure observed at the Wilcox Observatory.

Spectroscopic Velocity Observations

Large-scale motions in the solar convection zone probably play a crucial role in organizing the magnetic field. In any case, the distribution of magnetic active sites must certainly be intimately connected with the dynamics of the convection zone. Globally organized convective motions probably maintain differential rotation, drive the dynamo generating strong fields, and perhaps concentrate magnetic flux into active regions. However, the accurate measurement of such photospheric velocities has been seriously complicated by the difficulty of disentangling the Doppler contribution to observed line-shifts from the effects of strong magnetic fields and other solar motions.

Accurate determination of surface motions by Doppler shift measurements is fundamentally more difficult than apparently similar measurements of the magnetic field. This difficulty comes from the diversity of sources of line shifts and from the line-of-sight nature of the observations. While magnetic fields are nearly radial in the photosphere, velocities have significant components in all directions. Thus, to infer particular components one must make assumptions about spatial scales or lifetimes of the particular velocity structures of interest. For instance, in the case of east-west flows that should include both rotation and giant-cell information, one can either integrate over a portion of the disk for each day, or follow a specific point on the sun during its disc passage. We have used both techniques.

We have undertaken a search for giant cells in collaboration with H. Yoshimura of the University of Tokyo. Using the spatial averaging method, we found what appeared to be organized patterns of zonal (east-west) velocities centered on active regions (Scherrer et al., 1985; Yoshimura et al., 1985) in certain years of high activity. Upon subsequently comparing our data with the NSO high-resolution magnetic synoptic charts provided by J. Harvey, we established that most or all of the organized part of our signal can be reproduced by assuming a linear relation between the measured Doppler shift and the average field strength in the field of view (Scherrer et al., 1986). Our signal is consistent with a field-associated "downflow" of several hundred m/s. Using the spatial averaging technique in a line sensitive to the "downflows" there is no simple way to avoid this problem. We are investigating methods to use high-resolution magnetograms from the NSO to remove this contamination.

We also looked for the giant-cell signature by the disc-passage velocity vector decomposition method. In this case we found that the day-to-day velocity variance from 5-minute oscillations and the lack

of an absolute wavelength reference introduced too much noise in the east-west, non-rotation component of the signal. In this process of searching for giant cells we have refined our Doppler measurements by calculating residuals with respect to 54-day running means at each point on the disk. We find that by analysis of the sources of variance we are able to place upper limits to any long term variations in the zonal velocity. This is tantamount to setting limits on variations in the photospheric rotation rate (Bogart and Scherrer, 1986). Most of the variance in the day-to-day inferred components of horizontal velocity appears to be due to three factors: noise from five-minute oscillations, the contribution of magnetic fields, and variations in the dispersion and turbulence in the spectrograph due to environmental conditions. We find that of the total variance for one of our observed grid points has contributions from the various sources as follows:

Sources of Line Position Variance

	$(m/s)^2$	m/s rms
Instrument noise	174	13.2
5-Minute Osc.	66	8.1
Magnetic Fields	53	7.3
All Other	41	6.4
Total Observed	*334*	*18.3*

We are currently analyzing these effects, with a view to refining and enhancing our observing program and reduction procedures. An accurate assessment of these sources of noise is necessary for the proper evaluation of any claimed detections of large-scale velocity fields.

Budget Analysis

The research program described above can not be fully accomplished with the level of funding requested. We expect to obtain partial support for this and related work from other agencies with the ONR support contributing about one sixth of our total support. This support is however a very important part of our total effort and allows some emphasis on the aspects of our research that relate to the timing and severity of geomagnetic disturbances.

The budget includes funding for 15% of the effort of both Phil Scherrer and Todd Hoeksema with 5% support from Rick Bogart and about half of the support for Harald Henning. The budget shows modest travel and publications funds for reporting the expected results. The budget also includes funds for

maintanence and support of the observing effort at the Wilcox Observatory. To meet a constant funding level for the second year of this two year request we will need to find other support for more of the observatory maintenance.

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Report sent by electronic mail to Neil Sheeley in August 1987.

Notes on work by WSO group in past year for Neil Sheeley. These notes are not intended to be a complete progress report, but to point out areas where particular progress was made in the past year. I have grouped several topics under two main headings and discuss them briefly.

Methods of velocity measurement:

We have investigated methods appropriate to observe solar motions. We have examined both the traditional method of measuring line-of-sight Doppler-shift velocities and a new method of correlation tracking to measure horizontal velocities.

We have shown that for many purposes the traditional 2-point Doppler measurement technique provides incorrect results. In addition to the other well known problems affecting Doppler measurements of large scale convective flows (e.g. field associated red shifts, limb shift, noise from oscillations, super-granulation, granulation, etc) We have found that the dynamic range of the 2-point method is usually insufficient to measure large scale flows without bias. The problem is that the instrumental response is non-linear for large velocities. The sun has large velocities on the fine scale. If these fine scale features are to be properly averaged in large scale observations, they must contribute linearly. The error will be on the scale of active regions. To the extent that fields exhibit meso- and super-granulation scale motions the instrumental response function will be biased in such a way that granular motions will not be properly averaged. The detailed numerical simulation of this effect has not been completed, however quick calculations show that it will be an effect at the few m/s level of flow with scale size similar to supergranulation or active center dimensions. For future instruments, the Fourier Tach style of measurement is to be preferred.

We have also examined the telescope aperture and image quality required to successfully use the correlation tracking technique to measure meso- and larger-scale transverse velocities. We found that a modest 12cm telescope is sufficient if located in a place with no seeing.

Coronal rotation:

We have previously examined the latitudinal structure of the computed source surface fields. We found that most of the open flux that structures the corona is organize in two large structures rotating at slightly less than 27 days and slightly more than 28 days. We also examined the differential rotation and confirmed the nearly rigid rotation profile.

We now understand the rigid rotation of the corona to be an obvious byproduct of the evolution of large scale surface fields. We came to this conclusion simultaneously and idependently of the NRL group. The cause of the rigid rotation is that the coronal fields are primarily structured by the lowest order components of the surface fields an these surface field patterns rotate nearly rigidly. They rotate nearly rigidly because the patterns are the combined byproduct of surface zonal an meridional motions, and not simply of differential motions.

Another perspective, is: a) the coronal structure is formed by the lowest order components of the surface fields, and b) the lowest order components almost by definition have large latidudinal as well as longitudinal extent, and c) the power in the lowest order components is clumped into primarily two source regions (in latitude), one in the north rotating at about 26.9 days an one in the south at about 28.1 days. Since these two similar periods each control an overlapping range of latitude, the result is a rigid rotation of a slowly changing pattern. In fact, the pattern will change in something related to the beat period of these two periods.

Work also continues with the magnetic data and comparisons with coronal and space observations. Todd has just completed his part of a collaborative effort with Behannon et al to describe the evolution of the current sheet as tested be Voyager observations.

Proposal to

OFFICE OF NAVAL RESEARCH

To Renew Contract N00014-86-K-0085 on

GEOMAGNETIC DISTURBANCES

For the Period

October 1, 1988 to September 30, 1990

May 1988

Submitted by:

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(415)723-1504

Foreword

This is a proposal for continuation of the Geomagnetic Disturbance research and the operation/maintenance of the Wilcox Solar Observatory under the direction of Dr. Philip H. Scherrer as Principal Investigator at the Center for Space Science and Astrophysics at Stanford University, Stanford, California under Office of Naval Research Contract N00014-86-K-0085. Support is requested for a two year period beginning October 1, 1988, and ending September 30, 1990 in the amount of $80,000 per year.

Proposal for Continuation of Naval Research

Contract N00014-86-K-0085

GEOMAGNETIC DISTURBANCES

Introduction

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There is little doubt that magnetic field evolution is directly related to most if not all solar variability. Solar magnetic fields are organized on several spatial scales. While some of the solar variability is controlled by field changes on small-scales, the largest scales of organization are responsible for structuring the corona and solar wind expansion. It is also evident that small-scale activity is organized into larger-scale centers of activity. The development of an understanding of the relation between solar activity and the evolution of the large-scale patterns of fields is an important part of our research effort. Our solar magnetic field synoptic observing program is dedicated to obtaining data necessary to understand the source and evolution of the relevant fields. Our daily magnetograms are now used in daily forecasts by the NOAA Space Environment Laboratory.

The "static" structure of the corona is determined by the large-scale organization of photospheric fields. During times of low activity, these fields can be used to infer the coronal structure and the form of the heliospheric current sheet with reasonable accuracy. During times of high activity, the large-scale fields produce the ambient structure of the solar wind and interplanetary field into which transient material is injected. We are continuing our study of the origin and structure of coronal magnetic fields and the

origin of solar wind variability.

In addition to effects of the observed magnetic field structure, solar activity is apparently influenced by fluctuations in the global level of activity on time scales of months. These phenomena have only recently been recognized, and they are not yet understood or even completely described. Much of the work on them has been going on at Stanford, and we are beginning to be actively involved in this unexpected and very intriguing research.

A knowledge of the structure of the solar convection zone and the global circulation is crucial to understanding the large-scale organization of magnetic fields and the eventual understanding of the solar magnetic cycle. One of our observational efforts has been an attempt to directly observe the surface manifestations of giant scale convective motions. Our 12-year series of Dopplergrams provide upper limits to the observable amplitudes of these elusive motions.

Our recent progress and proposed investigations in each of these areas will be discussed below.

Large Scale Magnetic Fields

We propose to continue our successful observing programs of solar magnetic and velocities with an emphasis on fine-tuning the observing program to focus on questions of current interest without compromising the continuity with past observations that is so critical for a meaningful synoptic program. Our analysis will focus on the long term variability of the Sun and will increasingly emphasize correlative studies with other data including cosmic rays, the interplanetary magnetic field, coronal field and density measurements, and other photospheric observations of both magnetic and velocity fields.

We plan to continue our mean field measurements which are useful for solar wind prediction and as a long-period record of solar activity. In addition to the mean field, we have recently begun providing magnetograms to the solar forecast center in Boulder in near real time. The daily magnetograms will provide a useful tool in forecasting. We will also continue providing the magnetograms to P. McIntosh who finds them useful in preparing photospheric polarity maps based primarily on $H\alpha$ observations. We intend to pursue a study with P. McIntosh to study in more depth the relation of $H\alpha$ observations and our magnetograms. We plan to continue publishing the mean field, magnetograms, and synoptic charts in *Solar Geophysical Data*. Keeping up with requests for assorted data products requires a significant effort. We would

also like to publish an update to the Atlas we completed several years ago.

In the past couple of years we have completed several studies using WSO data and computations in correlative studies. One interesting project involved producing video disk 'movies' of various synoptic solar observations over an interval spanning roughly a solar cycle (Hoeksema et al., 1987). We combined photospheric fields from WSO and the Kitt Peak Solar Observatory, calculated fields from WSO, coronal green line intensities from Sacramento Peak, and coronal white light intensities from Mauna Loa in producing several movies that allowed intercomparison of the data sets at various speeds. We hope to continue making these movies and perhaps adding other data sets of interest (e.g. space based coronagraph data) as they become available. A great deal can be learned about the evolution of the structures on various time and size scales by watching the movies.

One investigation that is underway as a result of the 'movies' concerns the meridional transport of magnetic field. The characteristic backwards C-shape of large unipolar magnetic regions was very clear when watching the movies. The patterns appeared to develop from emerging flux regions and spread rapidly to higher latitudes and a great range in longitude, much as smoke rises on a windy day. We are pursuing that analogy to determine the meridional transport required to produce the patterns observed.

A long set of synoptic data provides an opportunity to look for variations in quantities over a sunspot cycle. For example, how does the photospheric magnetic field rotate and how does that rotation vary with time? We looked at the variation of the computed coronal field (Hoeksema & Scherrer, 1987) and have to traced the different rotation rates observed in the two hemispheres back to the photospheric source. We find a significantly different rotation rate of the large scale field in the northern and southern hemispheres during most of solar cycle 21. That result is confirmed by analyzing the field data from NSO for cycle 21. Cycle 20 data from Mt. Wilson suggests that a similar effect may have been present in earlier cycles.

Work by DeVore, Sheeley, and colleagues (DeVore & Sheeley, 1986; Sheeley et al., 1987) has shown that in the absence of new sources of flux, the magnetic field patterns will produce a pattern rotating rigidly with a period of about 28 days. The appearance of new sources at lower latitudes produces a rotation nearer the equatorial rate of 27 days. These are the two rotation periods observed in the photosphere, corona, and in the interplanetary medium, for as many a 6 cycles in the case of the inferred IMF polarity. The relation between these rotation rates, the organization of the solar cycle, and the appearance of flux are

topics of continuing study.

Coronal and Interplanetary Magnetic Fields

Our computations of the coronal magnetic field from the photospheric observations will also continue. Because the solar wind originates in the corona, the field pattern there predicts the polarity pattern observed in the interplanetary medium. In the past the model field was periodically updated and was only used as a predictive tool once, during the time of the Comet Halley redezvous with several spacecraft. Recently the computation of the source surface field has been largely automated and somewhat revised. In the past we used a conservative scheme in reducing the data, one which constructed the synoptic charts and source surface field only after the point of interest had finally disappeared over the limb of the sun. We have now added the capability to update the reduction after the first observation of the field rather than the last. This adds at least 110 of solar longitude to our analysis and actually allows a prediction of the coronal field up to four days before it reaches central meridian. We currently update the calculation weekly, but plan to increase the frequency of reduction if there is sufficient interest. Having the ability to perform the data reduction immediately upon completion of an observation is one of our goals in the near future. We are currently providing the updated source surface field each week to Greg Deuel of the Air Force Geophysical Weather Service and hope to expand the distribution of the data to others who are interested.

One of the difficulties in automating the calculation of the potential field model was determining the strength of the polar field correction. It was realized early on that the model did not accurately reproduce the configuration of the magnetic field in the corona using the directly measured field. Analysis by Svalgaard et al. (1978) of the early data from the Wilcox Solar Observatory revealed the presence of a large polar field in the annual variation in field strength of the polemost observed aperture. While large (about 11 Gauss), the derived field was very sharply peaked. Furthermore the inclusion of this field produced a good agreement between calculations of the coronal field, interplanetary field observations, and observations of coronal electron densities. This polar field remains constant near solar minimum but changes fairly rapidly near solar maximum as the polarity of the solar polar field reverses. Until recently we used the value of the measured field to roughly scale the original field strength. That procedure was quite subjective and was last performed in 1984. Since that time the polar field has increased significantly in magnitude,

necessitating a recomputation of the model to more accurately reflect our new approximation of the field. The latitudinal amplitude of the current sheet has been revised downward from our original calculations for 1984 to the present. The polar field estimate is now updated each time the computation is made.

This determination of the polar field correction is not very satisfying, in part because of the apparent discrepancy between polar field strengths measured by various solar observatories. Because the aperture at WSO is so large (3 arc minutes) there is very poor resolution in the polar regions. The polar field strengths observed elsewhere with higher resolution telescopes are not as large. There are also differences in the way field strengths are observed to fall off with distance from the center of the disk that may be related to this problem. We propose to investigate and resolve these apparent discrepancies.

We completed an investigation of the change in structure of the heliospheric field with increasing distance from the sun and changing heliographic latitude using coronal field calculations and IMF measurements at Venus, Earth and farther out in the solar system as obtained by the Voyager spacecraft. (Behannon et al., 1988) We found that with increasing distance from the sun the ordered sector structure begins to break down. At Venus the computed and observed structure were very highly correlated. At Earth the correlation was also good, though slightly lower. As the Voyager spacecraft reached greater and greater heliocentric distances the stability of the sector structure decreased. From one rotation to the next there was very little correlation between the observed patterns. The two spacecraft at different latitudes also observed different structures. The simpler the structure near the sun, the more likely it was to maintain its integrity out to the Voyagers. One interesting feature was the disappearance of the sector structure at Voyager 2 which was at high latitudes at about the time predicted by the coronal field model.

Cosmic rays are also influenced by the configuration of the heliospheric fields. Building on work begun in 1986 (Christon, Stone & Hoeksema), Lockwood, Webber, and Hoeksema (1988) went on to investigate the latitudinal gradient in cosmic rays from 1984 to 1987. We found a dependence of cosmic ray intensity observed between IMP-8 and Voyager 2 of up to -1.5% per degree as the tilt of the current sheet decreased late in the solar cycle. These results do not fully coincide with the predictions of cosmic ray transport models; much work remains to be done to understand the interaction of the current sheet and cosmic rays. Further data from Voyager 2 at high heliographic latitudes and the eventual results from the Ulysses spacecraft will be of great help in determining the structure of the current sheet at high latitudes.

Activity Centers and the Solar Cycle

New evidence of the nature of the solar cycle has recently appeared from time series analysis of solar activity. In particular, periodicities in the occurrence of major flares suggest both short-term periodicities of 152 and 51 days in the global activity level (Rieger et al, 1984; Bogart & Bai, 1985; Bai, 1987; Bai and Sturrock, 1987) and the presence of hitherto unsuspected active areas rotating at different rates (Bai, 1988), at least for the last two cycles.

We have assembled several useful data sets, including the geomagnetic activity indices, the detailed Greenwich sunspot data from 1874--1976, and the Kitt Peak and Mt. Wilson synoptic magnetic data since 1974 in addition to the data from the WSO. We are proposing to examine these data sets for evidence of the periodicities and "hot spots" found by Bai. In particular we want to understand the relationship between the the large scale fields and the active centers that Bai finds rotating at essentially the same rates that we find for the large scale field patterns. A first look at the relation between the locations of the active centers and our large scale field maps did not reveal a simple relationship.

Direct Velocity Observations

We are convinced that a true understanding of the source and evolution of solar activity must await an understanding of solar convection. Studying the large scale circulation indirectly by following the evolution of magnetic field patterns was discussed above. A difficulty with such indirect methods is that one is never quite sure what is being observed. While most of the large scale convection that probably drives the solar cycle takes place below directly observable depths, there are three opportunities to examine convection directly.

The traditional method is direct line-of-sight Doppler shift observations. To date, these observations have yielded only upper limits for large scale convection and circulation. There is some evidence of flows at about the 10m/s level, but these observations are at the limit of detection due to various sources of solar and instrumental noise and due to contamination from the effects on line profiles probably due to small scale convection differences between magnetic and non-magnetic regions. Since we have now accumulated more than 12 years of daily Doppler shift observations, we plan to continue our analysis of this data. The primary problem at this point is to improve methods to at least identify which data is contaminated by

the presence of fields and possibly to make a first order correction. We now have recieved NSO magnetograms for all our intervals of good observations so we can use the actual magnetic fields to model the effect on our Doppler observations. We must use these high resolution magnetic observations to properly model the effect on the integrated line profile. The immediate goal of this study is to discover what fraction of our Doppler signal is actually due to the effects of fields.

The second method to directly study solar circulation is to observe the horizontal advection of small scale structures. This can be done by correlation tracking of granulation. Bogart et al. (1988) have demonstrated the feasibility of using this technique with the Michelson Doppler Imager (MDI) experiment that we are building for the NASA SOHO mission. While direct application of this method in an operational sense is probably many years away, we will continue to track and participate in its development as a diagnostic tool.

The third method is inference of internal motions using the techniques of helioseismology. Our MDI program is designed to do just that. While that program will not produce observations for several years, we will continue to develop techniques to use the eventual data to address the questions of large scale solar circulation.

Budget Analysis

The research program described above can not be fully accomplished with the level of funding requested. We expect to obtain partial support for this and related work from other agencies with the ONR support contributing about one fifth of our total support for the operation of the observatory and the research program of which the above described programs are a part. This support is however a very important part of our total effort and allows some emphasis on the aspects of our research that relate to the timing and severity of geomagnetic disturbances.

In addition to the operation of the observatory and the related research program. I am the PI for the NASA sponsored Solar Oscillations Imager experiment for the SOHO mission. While this program will eventually yield important observations concerning the solar interior, at present most of that effort is related to the development of the flight hardware rather than research activities.

The budget includes support for about one month for myself and Todd Hoeksema in each year. In FY 89 it also includes about the same level of support for Taeil Bai from Peter Sturrock's group. This will facilitate a closer collaboration on those aspects of our programs which have common objectives. We are also requesting partial support for a graduate student who is our chief observer. The budget shows modest travel and publications funds for reporting the expected results. The budget also includes funds for maintanence and support of the observing effort at the Wilcox Observatory.

We are requesting capital equipment funds in the first year to purchase a CD-ROM reader to allow access to the full geomagnetic data as distributed by the NOAA National Geophysical Data Center. We are requesting capital equipment funds in the second year to replace the MODEMs that connect the observatory data acquisition computer with the analysis computer on campus.

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